Domain Driven Distributed Reference Architecture For Big Data Systems

Pouya Ataei, Alan Litchfield

[a]*School of Engineering, Computer and Mathematical Sciences, Auckland University of Technology, Auckland, New Zealand*

Abstract

The ubiquity of digital devices, the infrastructure of today, and the ever increasing proliferation of digital products have dawned a new era, the era of big data. This era began when the volume, variety and velocity of data overwhelmed traditional systems that used to analyze and store that data. This precipitated a new class of software systems, namely big data systems. Whereas big data systems provide competitive advantage to businesses, many failed to harness to power of it. It has been estimated that only 20% of companies have successfully implemented a big data project. This is due to various challenges of adopting big data such as organizational culture, rapid technology change, system development, data architecture and data engineering. This paper aims to facilitate big data system development, architecture and data engineering by introducing a domain driven decentralized big data reference architecture. This artefact is developed following the guidelines of empirically grounded reference architectures, and has been evaluated in a real world scenario. At the end, a prototype of the artefact has been instantiated and utilized to solve a real problem in practice. Our results displayed a good degree of applicability and some thought-provoking architectural tradeoffs and challenges.

Keywords: `Reference architecture, Architecture, Big data reference architecture, Big data architecture, Big data systems, Big data software engineering, Event driven, Microservices`

1. Introduction

Since the dawn of internet and world wide web, humanity has witnessed a degree of connection beyond reckoning. The proliferation of digital devices pervaded with powerful software applications have created cyber communities that constantly mutate [1]; [2]. In a world where we have network infrastructures that can support up to 250Mbps of data transmission, and smart phones and IOT devices that can have processing power of up to 3 Ghz, data becomes ubiquitous, the quantum that lays the foundation of the nexus [3].

According to InternetLiveStates.com [4], only in one second, there are 9,878 tweets sent, 1,138 instagram photos uploaded, 3,117,720 emails sent, 99,738 Google searches made, and 94,144 Youtube videos viewed. That is, if it has taken 5 second to read the preceding paragraph, during that time, 15,588,600 emails are sent.

Driven by the ambition to harness the power of this deluge of data, the term 'Big Data' (BD) was coined [5]. BD initially emerged to address the challenges associated with various characteristics of data such as velocity, variety, volume and variability [2]. BD is the practice of extracting patterns, theories, and predictions from a large set of structured, semi-structured, and unstructured data for the purposes of business competitive advantage [6]; [7]. BD is a game-changing innovation, heralding the dawn of a new data-oriented industry.

Nonetheless, BD is not a magical wand that can enchant any business process. While a lot of opportunities exist in BD, subsuming an emergent and rather high-impacting technology like BD to current state of affairs in organizations, is a daunting task. According to recent survey from Databricks, only 13% of the organizations excel at delivering on their data strategy [8]. Another survey by NewVantage Partners indicated that only 24% organization have successfully gone data-driven [9]. This survey also states that only 30% of organizations have a well established strategy for their BD endeavour. In addition, surveys from McKinsey & Company ([10]) and Gartner ([11]) further support these numbers, which illuminates on the scarcity of successful BD implementations in

the industry.

Among the challenges of data adoption perhaps the most highlighted are 'data engineering complexities', 'BD architecture', 'rapid technology change', 'lack of sufficiently skilled data engineers', and 'organization's cultural challenges of becoming data-driven' [2];[12]. This focus of this study is on data engineering complexities and in specific BD architecture.

In the past, organization relied on a few technology giants to provide infrastructure and tools necessary for BD, while today there's a plethora of choice from hundreds of providers covering different aspect of data ecosystem from ingestion, to logging, to stream processing, and to visualization [9]. Companies are tending more and more towards cloud native architectures for cost reduction, improved efficiency, which in turn resulted in creation of new roles such as chief analytics officer (CAOs) amd chief data officers (CDOs) to channel the organizational BD capabilities toward business value and competitive advantage [13].

So how can one embark on this rather sophisticated journey? what can be a good logical approach to absorb the ever-increasing complexity of BD systems? how can organizations build different stacks to handle data for various workloads such as machine learning (ML), business analytics, data engineering, and streaming?

We posit that majority of the challenge discussed starts with data architecture [1]; [3]. The data ingestion, processing and consumption of different data workloads vary, and sometimes they don't go well together. A company that enacted a data lake and a data warehouse and tries to account for both ecosystems, can be dealing with immense complexity, which in turns impact data teams, which in turn can hinder innovation, create barriers and result in monumental loss.

Development and deployment of an efficacious BD system is only the beginning of a BD journey. As data sources increase, variety of data increases, number of data consumers increase, the data store gets confuscated, and this can introduce threats for scalability and maintainability of the system. This

also implies that only a handful of hyper-specialized data engineers would understand the system internals, creating silos, and potential miscommunication.

Majority of these systems are developed on-premise as ad-hoc complicated solutions that do not adhere to the practices of software engineering and software architecture [14]; [15]. As the ecosystem grows and new technologies and data processing techniques are introduced, the software architect will have a harder time to come up with a solution that address the problem requirements.

This can potentially create grounds for an immature architecture that results in solutions that are hard to scale, hard to maintain, and raise high-entry blockades [3]. Since the approach of ad-hoc design to BD system development is not desirable and may leave many architects and data engineers in the dark, novel data architectures that are designed specifically for BD are required. To contribute to this goal, we explore the notion of reference architectures (RAs) and present a distributed domain-driven software RA for BD systems.

2. Why reference architecture?

To justify why we have chosen reference architectures as the suitable artefact, first we have to clarify two assumptions;

1. having a sound software architecture is essential to the successful development and maintenance of software systems
2. there exist a sufficient body of knowledge in the field of software architecture to support the development of an effective RA

One of the focal tenets of software architecture is that every system is developed to satisfy a business objective, and that the architecture of the system is a bridge between abstract business goals to concrete final solutions [16]. While the journey of BD can be quite challenging, the good news is that a software RA can be designed, analyzed and documented incorporating best practices, known techniques, and patterns that will support the achievement of the business goals. In this way, the complexity can be absorbed, and made tractable.

Practitioners of complex systems, software engineers, and system designers have been frequently using reference architectures to have a collective understanding of system components, functionalities, data-flows and patterns which shape the overall qualities of system and help further adjust it to the business objectives [17]; [18]. There is a fair amount of literature on reference architectures, and whereas different authors definition may vary, they all share the same tenets.

A reference architecture is amalgamation of architectural patterns, standards, and software engineering techniques that bridge the problem domain to a class of solutions. This artefact can be partially or completely instantiated and prototyped in a particular business context together with other supporting artefact to enable its use. RAs are often created from previous RAs [1].

The usage of RAs for the development of complex systems is not new. In software product line (SPL) development, RAs are generic artifacts that are configured and instantiated for a particular domain of systems [19]. In software engineering, major IT giants like IBM has referred to RAs as the 'best of best practices' to address unique and complex system development challenges [17].

Based on the premises discussed and taking all into consideration, RAs can facilitate the issues of BD architecture and data engineering because of the following reasons;

1. RAs can promote adherence to best practice, standards, specifications and patterns
2. RAs can endow the data architecture team with openness and increase operability, incorporating architectural patterns that ensue desirable predefined quality attributes
3. RAs can be the best initial start to the BD journey, capturing design issues when they are still cheap
4. RAs can bring different stakeholders on the same table and help achieve consensus around major technological constructs
5. RAs can be effective in identifying and addressing cross-cutting concerns

6. RAs can serve as the organizational memory around design decisions, enlightening next subsequent decisions
7. RAs can act as a summary and blueprint in the portfolio of software engineers and software architects, resulting in better dissemination of knowledge

3. Research Methodology

There are a few studies that have addressed the systematic development of reference architectures. Cloutier et al [17] present a high-level model for RA development through collection of contemporary information and capturing the essence of architectural advancements. In another effort, PuLSE-DSSA is proposed by Bayer et al. [20] in the context of product line development and domain engineering. PulSE-DSSA emphasizes on capturing the existing architectural knowledge. Stricker et al. [21] propose a pattern-based approach for creating an RA. This study revolves around software engineering patterns motivated by the work of Gamma et al [22]; and proposes a structural approach that includes three layers of patterns with well-defined hierarchical relationships. Nakagawa, Martins, Felizardo, and Maldonado [23] propose an approach to RA design outside of product line management context that is concentrated towards aspect-oriented systems.

Galster and Avgeriou [24] propose an empirically grounded reference architecture based on two main facets; Existing RAs in practice and available literature on RAs. Along the same vein, Nakagawa et al [25] presented ProSA-RA which is a 4 phase methodology that unlike many other methodologies do provide a more comprehensive instructions on RA evaluation. In addition, this methodology benefits from an ecosystem of complementary constructs that aid in RA design and evaluation such as RAModel [26] and a framework for evaluation of RAs (FERA) [27].In a recent study, Derras et al. [28] propose a schema of practical RA development in the context of software product line and domain engineering. This study is based on capturing knowledge from architectures in

practice with attention to variability, configurability and product line development. The findings provide a four-phase process to develop quality driven reference architectures. This approach is influenced by ISO/IEC 26550 [29].

By analysis and study of all these approaches for design and development of RAs, a common pattern has been witnessed. Whereas some of them are more recent and some belong to years ago, there are commonalities that has been observed. All these approaches are grounded on three main pillars, 1) Existing RAs 2) RAs in literature 3) Architectures in practice. Taking this into consideration and by analyzing the results of the systematic literature review conducted by Ataei et al [1] we found 'Empirically-grounded reference architectures' proposed by Galster and Avgeriou [24], a suitable methodology, because firstly it's been adopted by many studies, and secondly it's comparatively in-line with the nature of our study.

Nevertheless, we did not fully adopt this methodology and rather customized to the needs of this particular research. This is due to some inherent limitations that has been witnessed with the methodology. For instance we could not find a comprehensive guideline on how to identify data sources and how it could be categorized and synthesized into the creation of the RA in the third step of the methodology, therefore we employed the Nakagawa's information source investigation guidelines and the overall idea of the RAModel. Another limitation we've faced was with evaluation of the RA. As evaluation, second to a sound research methodology is one of the key elements of any good design science research, we had to look for a stronger and more systematic evaluation approach than what was discussed in 'empirically grounded RAs' methodology. For this purpose, and inspired by the works of Angelov et al [30]; [31], we first created an prototype of the RA in practice, and then used 'The architecture tradeoff analysis method' (ATAM) [32] to evaluate the artefact.

This research methodology is constituent of 6 phases which are respectively; 1) Decision on the type of the RA 2) Design strategy 3) Empirical acquisition of data 4) Construction of the RA 5) Enable RA with variability 6) Evaluation of the RA. The phrase 'empirically grounded' refers to two major elements;

firstly the reference architecture should be grounded in well-established and proven principles; secondly, the reference architecture should be evaluated for applicability and validity. These don't only belong to Galster and Avgeriou methodology, and other researchers such as Cloutier [17] and Derras et al [19] have promoted the same ideas.

It is worth mentioning that this methodology is iterative, meaning that the results gained from the evaluation phase (6th phase) determines the subsequent iterations until the design reaches saturation.

3.1. Step1: Decision on type of the RA

Precursor to any effective RA development, is the decision on type of it. The type of the RA is significant, as it illuminates on information to be collected and the construction of the RA in later phases. The selection on the type of RA for the purposes of this study is based on two dimensions; the classification framework proposed by Angelov et al. [33] and the usage context [34].

Based on the classification framework proposed by Angelov et al. [33], five types of RA are defined. This framework has been developed with the goal of supporting analysis of RAs with regards to context, goal, and the architecture specification/design relationships. It is based on 3 major dimensions namely context, goals, and design, each having their own corresponding sub-dimensions. These dimensions and sub-dimensions are derived by the means of interrogatives (the usage of interrogates is a well-established practice for problem analysis).

The interrogatives 'When', 'Where', and 'Who' have been used to address the 'context', 'Why' has been used to address 'goal', and 'How' and 'What' have been used to address 'design' dimension. The outcome of the study categorizes RAs in two major groups; 1) standardization RAs and 2) Facilitation RAs. This framework has been chosen because it is completely in-line with the purposes of this study and aims to demarcate a clear domain for the RA to be developed. The comprehensive classification of the RAs with examples in practice illuminates on how different RAs are playing roles in the industry and how they are classified. This brings clarity on what should be developed and what boundaries

should be drawn.

By reading the results of the recent SLR conducted by Ataei et al on BD RAs [1], we've added more examples of the RAs on top of what was provided by Angelov [33], and provided the following updated list of RA classifications with examples;

1. Standardization RAs
   (a) Type 1: classical, standardization architectures designed to be implemented in multiple organizations. Examples are:
      i. WRM [35]
      ii. OSI RM [36]
      iii. OATH [37]
      iv. COBRA [38]
      v. Neomycelia [3]
      vi. Kappa [39]
      vii. Bolster [15]
   (b) Type 2: classical, standardization architectures designed to be implemented in a single organization
      i. Fortis Bank Reference Software Architecture [33]
2. Facilitation RAs
   (a) Type 3: classical, facilitation reference architectures for multiple organizations designed by a software organization in cooperation with user organizations
      i. Microsoft Application Architecture for .Net [40]
      ii. IBM PanDOORA
      iii. OATH [37]
      iv. COBRA [38]
   (b) Type 4: classical, facilitation architectures designed to be implemented in a single organization
      i. Achmea Software Reference Architecture [41]
      ii. ABN-AMRO Web Application Architecture [42]

(c) Type 5: preliminary, facilitation architectures designed to be implemented in multiple organizations
   i. ERA [34]
   ii. AHA [43]
   iii. eSRA [44]

The domain driven distributed BD RA chosen for the purposes of this study pursues two major goals; 1) enabling and support the development and data engineering of BD systems 2) concurrently ensuring that interoperability between different heterogeneous components of the BD system is established. Therefore, the outcome artefact will be a BD RA that is a classical standardization RA designed to be implemented in multiple organizations. jmk

3.2. Step2: Selection of Design Strategy

Angelov et al [30] and Galster et al[24] have both presented that RAs can have two major design strategies to them; 1) RAs that are designed from scratch (practice driven), 2) RAs that are based on other RAs (research driven). Designing RAs from scratch is rare, and usually takes place in an emergent domain that have not perceived a lot of attention. On the other hand, most RAs today are the amalgamation of a priori concrete architectures, models, patterns, best practices, and RAs, that together provide a compelling artefact for a class of problems.

RAs developed from scratch tend to create more prescriptive theories, whereas RAs developed based on available body of knowledge tends to provide with more descriptive design theories. The RA designed for the purposes of this study is a research-based RA based on existing RAs, concrete architectures, and best practices.

3.3. Step 3: Empirical Acquisition of Data

As aforementioned, due to the limitation witnessed by this research methodology, we have augmented this phase, and increase the systematicity and transparency of data collection and synthesis through various academic methods such as systematic literature review or SLR.

This phase is made up of three major undertakings; 1) identification of data sources; 2) capturing data sources; 3) synthesis of data sources.

3.3.1. Identification of data sources

To identify suitable data sources, we've employed the first step of ProSA-RA methodology, 'information source investigation'. This step is an endeavour to capture focal and ancillary knowledge and theories that revolve around the target domain, and lay the ground of RA development.

To unearth the architectural quanta, and to highlight gradations between various approaches to BD system development, we've selected most relevant sources as the followings;

1. **Practice-led conferences:** given that majority of recent advancements for emerging technologies such as microservices architecture [45];[46] [47] and BD are coming from virtually hosted practice-led conferences, we've chosen some of the best conferences hold world-wide for the purposes of data collection. These conferences are 1) Qcon [48] 2) State of Data Mesh by ThoughtWorks [49] 3) Worldwide Software Architecture Summit'21 [50] and 4) Kafka Summit Europe 2021 [51]. Our objective was to capture the frontiers of software architecture and emerging approaches currently being practiced in IT giants such as Google, Facebook and Netflix. Among all the speech in these conferences, we looked for topics that entailed or were related to the keywords 'emergent software architecture trends', 'distributed software architecture', and 'BD software architecture'. We used the software Nvivo to code the transcripts from the conference videos. We used the aforementioned keywords as the codes and associated different texts, summative, essence-capturing sentences, evocative attributes to them. During this process, a new theme 'domain driven design' emerged. We added that into the list of codes as well.
2. **Publications:** in order to capture evidence from the body of knowledge, we conducted a systematic literature review (SLR), following the guidelines of PRISMA presented by Moher et all [52]. The main objective of

this SLR was to highlight common architectural constructs found among all the BD RAs. This SLR is build on top of our recent work [1] that covered all the RAs by 2020.

The initial SLR included IEEE Explore, ScienceDirect, SpringerLink, ACM library, MIS Quarterly, Elsevier, AISel as well as citation databases such as Scopus, Web of Science, Google Scholar, and Research Gate. The SLR search keywords used were 'Big Data Reference Architectures', 'Reference Architectures in the domain of Big Data', and 'Reference Architectures and Big Data'. We followed the exact methodology, but this time for the years 2021 and 2022. Our aim was to find out if there has been any new BD RA published during the years mentioned.

By the result of this SLR, we've found 3 more BD RAs ([3]; [53]; [54]) and we've added two new standards ([55]; [56]) to further solidify our study. Converging these new SLR with the old, covering the years 2010-2022, we've pooled 89 literature in the primary phase, and another 10 by snowballing and citation searching. These 99 literature then went through our inclusion, exclusion and quality criteria. These criteria is as blow;

- Inclusion criteria:
  (a) studies that entailed real-world scenarios or tend to solve a problem in practice
  (b) qualitative or quantitative researches that intended to solve the industry gaps in big data system development and architecture
  (c) studies that had strong evaluations, preferably those that created the artefact in an actual organizational setup
  (d) explores the concept of RAs
  (e) provides or builds up on thorough discussion on BD RAs, limitations, drivers, and the overall ecosystem
  (f) is recent, within the years specified
  (g) is a conference paper, journal paper, book, book chapter, white paper, dissertation or thesis
- Exclusion criteria:

(a) the study is not well evaluated or practice driven

(b) is a duplicate

(c) the study is not in-line with research objectives

(d) not written in English

(e) provides a poor quality or misleading technical information

- EQuality assessment:

  (a) is the study rich in terms of relevance to practice?

  (b) does the study create related design/design science or kernel theories?

  (c) does the study entail sufficient data?

  (d) does the study discuss the recent trends in BD domain?

  (e) is the study based on primary data and is internationally focused?

3.3.2. Data Synthesis

After pooling the studies, we removed 11 studies before screening because either they were duplicates or they were not in English. The remaining 78 studies went through screening, in which, 2 studies excluded based on the exclusion criteria. From there on, 76 studies have been assessed for eligibility based on the quality framework and the inclusion criteria. The result of this process handed over 67 studies from this branch. From the other branch, 10 records identified through citation searching. These reports have been assessed through the same quality framework, inclusion and exclusion criteria, which yielded 5 studies from this stream. Together 68 studies pooled for this SLR as depicted in figure 1.

These 68 studies are comprising of journal papers, conference papers, book chapters, tech reports, tech surveys white papers, standards, master dissertation, and PhD thesis. Out of the pool of these studies, 39.4% are from IEEE Explore, 4.4% are from ScienceDirect, 23.5% are from Springerlink, 13.2% are from ACM, and 29.4% are from other sources such as citation search, Google Scholar and Research Gate. 30 journal articles, 14 conference papers, 6 whitepapers, 2 ISO standards, 14 book chapters, and 2 postgraduate studies have been

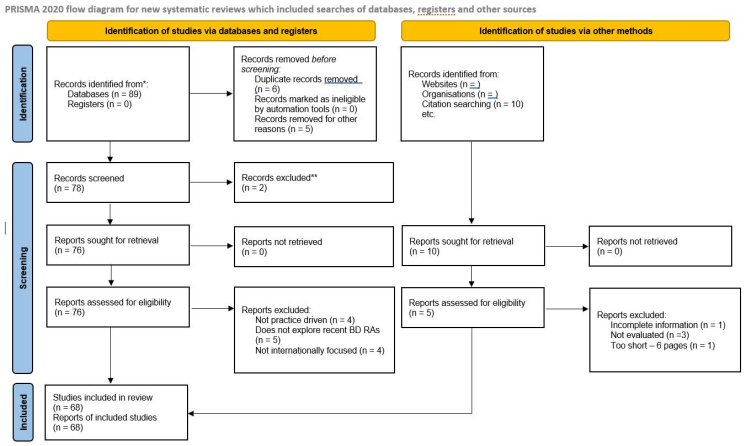

Figure 1: PRISMA flowchart

selected. 26% of these studies are from the year 2010-2013, 33% are from the years 2013-2015, and 51% are from the years 2016-2022. These stats are portrayed in figure 2.

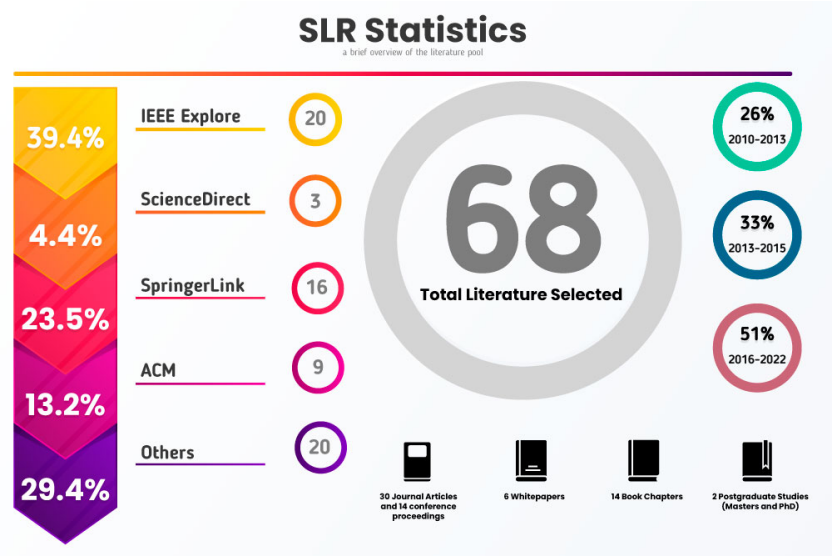

Figure 2: SLR statistics

By this stage, the research objective is set, studies are pooled, assessed and

refined, thus the research embarked on the actual synthesis of data. To increase transparency, RAs and standards found as the result of this SRL is presented in table 1. For this purposes, the software Nvivo [57] has been used to code, label, and classify studies. Initially, all the keywords aforementioned has been created as nodes in the software, which are then associated to relevant sentences in studies. After coding all the studies, the findings have been synthesized to create theories, which in turn emerged themes and patterns. The findings gained from this SLR grounded the foundation for various aspect of the SLR development.

Study	Author	Year	Type
Towards a big Data reference architecture	[58]	2013	Master's Dissertation
A reference architecture for Big Data solutions introducing a model to perform predictive analytics using Big Data technology	[59]	2013	Conference Paper
IBM - Reference architecture for high performance analytics in healthcare and life science	[60]	2013	Book
Big data ecosystem reference architecture	[61]	2013	White Paper
A proposal for a reference architecture for long-term archiving, preservation, and retrieval of Big Data	[62]	2014	Conference Paper
Questioning the Lambda architecture; Kappa Architecture	[39]	2014	Blog
Defining architecture components of the Big Data Ecosystem	[63]	2014	Conference Paper

Oracle - Information Management and Big Data: A Reference Architecture	[64]	2014	White Paper
Big Data driven e-commerce architecture	[65]	2015	Journal Article
The solid architecture for real-time management of big semantic data	[66]	2015	Journal Article
Reference architecture and classification of technologies, products and services for big data systems	[67]	2015	Journal Article
A Reference Architecture for Big Data Systems	[68]	2016	Conference Paper
A reference architecture for Big Data systems in the national security domain	[69]	2016	Conference Paper
A Reference Architecture for Supporting Secure Big Data Analytics over Cloud-Enabled Relational Databases	[70]	2016	Conference Paper
SAP - NEC Reference Architecture for SAP HANA & Hadoop	[71]	2016	White Paper
Managing Cloud-Based Big Data Platforms: A Reference Architecture and Cost Perspective	[72]	2017	Journal Article

Scalable data store and analytic platform for real-time monitoring of data-intensive scientific infrastructure	[72]	2017	PhD Dissertation
A software reference architecture for semantic-aware Big Data systems; Bolster Architecture	[73]	2017	Journal Article
Simplifying big data analytics systems with a reference architecture	[54]	2017	Conference Paper
ISO/IEC/IEEE 42010:2011	[74]	2017	Standard
NIST Big Data Interoperability Framework: Volume 6, Big Data Reference Architecture	[75]	2018	White Paper
Towards a secure, distributed, and reliable cloud-based reference architecture for Big Data in smart	[18]	2019	Book Chapter
Reference Architectures and Standards for the Internet of Things and Big Data in Smart Manufacturing	[76]	2019	Conference Paper
Lambda architecture	[77]	2019	Conference Paper
ISO/IEC 20546:2019	[55]	2019	Standard
ISO/IEC TR 20547-1:2020	[56]	2020	Standard
NeoMycelia: A software reference architecturefor big data systems	[3]	2021	Conference Paper

Smart transportation: A reference architecture for big data analytics	[53]	2021	Journal Article

Table 1: RAs and Standards found by the result of the SLR

3.4. Construction of the RA

Based on the themes, theories, and patterns realized in the previous steps, the process of RA construction took place. Integral to this step was the identification of elements that the RA should contain, how these elements should be synthesized, and how the RA can be portrayed and communicated. To describe our RA, we followed ISO/IEC/IEEE 42010 standard [74]. This standard pivots on concrete architectures, so we did not 100% conform to it, but rather the good and relevant parts of it has been taken. For instance, architecture viewpoints, statement of corresponding rules, and expression of the architecture through architecture description languages (ADLs) have had direct impact on the construction of this RA.

A key challenge in the development of this RA was to strike a balance between the specificity of the micro patterns and approaches to system development and general architectural concepts that reflect a view of the system as an array of interrelated entities. Angelove et al [78] approached this problem by the means of interrogative through a defined framework that aims to guide the creation of RAs. Cloutier et al [17] suggest that a RA should entail technical, business and customer context views, whereas Vogel et al [79] provided classifies RA views based on the usage context, as industry specific, platform specific, industry crosscutting and product line RAs.

Stricker et al [80] expressed their pattern-based RA by adhering several distinct views into one. Chang et al [75] presented NIST BD RA as a system constituent of logical components connected though interoperability interfaces in several fabrics. On the other hand, ISO/IEC/IEEE 42010 refrains from using

phrases such as “technical architecture”, “physical architecture”, or “business architecture”.

Taking the best evidence from the available body of knowledge, We decided to adhere several views into one and express the RA through a multi-layer modeling language called Archimate. Archimate is a mature modeling language developed by Open Group that provides with a uniform representation of high-level architectural diagram aimed at portraying and delineating enterprise architecture [81]. Archimate being listed as a standard architecture description language in ISO/IEC/IEEE 42010, is designed based on a set of related concepts that are specialized towards the system at different architectural layers. This means that the architect is enhanced with an integrated architectural tool that visualizes and describes different architecture domains and their underlying relations [82]; [83].

Archimate utilizes service-orientation to distinguish and relate the application, business and technology layer and use realization relationships to create relationship between concrete elements and more abstract elements across three layers. In addition, Archimate can be customized to account for varying needs of the architect.

3.5. Enabling RA with variability

Enabling RA with variability is an important process that helps with the instantiation of it. This allows RA to remain useful as a priori artefact when it comes to organization-specific regulations, and regional policies that constrain the architect design decisions [84].

Variability management has been studied in the domain of Business Process Management (BPM) [85]; ;[86]; [87] and Software Product Line Engineering (SPLE) [88][89]; [90]; [91]; [92]. In BPM, variability management revolves around efficient handling of different variants in business processes, whereas in SPLE, variability management is about modifying and extending the software artefact to account of the requirements of a specific context.

Clear identification of variability and explicit communication of it improves

communication between stakeholders, allows for traceability between variation causes and effects and facilitates the decision making [93].

Variation points are decided based on the data collected in previous steps. Galster et al [24] sugguest that there are three approaches to enabling variability;

1. Annotation of the RA
2. Variability views
3. Variability models

We could not find an in-detail explanation of how one should choose the appropriate variability enabling approach. Therefore, inspired by the works of Rurua et al [84], we decided to extend the RA with variability, by the means of Archimate annotations. We have achieved this in two steps; first we developed a custom layer that represents focal variability concepts, and then we extended the RA through annotation. The aim of this process is not find all variability points that may emerge in the usage context, but to provide with high-level system related architectural variabilities that an architect may consider for improvement of design and adoption of the RA.

The variability model is depicted in Fig 3 by the means of Archimate's motivation layer. This modeling is driven by the works of Pohl et al [88] and in specific their graphical notation of variability information, and Rurua et al [84] and in specific, their variability management concepts model.

3.6. Evaluation of the RA

Evaluation of the RA is to ensure that it has achieved the goals stated prior to development, to test is effectiveness and usability, and to make sure that it addresses the identified problems. Two fundamental pillars of the evaluation is the correctness and the utility of the RA and how efficient it can be adapted and instantiated [24]. The quality of RA can be assessed by how it can be transformed into an effective organization-specific concrete architecture. The fact that this RA is built upon former RAs helps making the evaluation steps

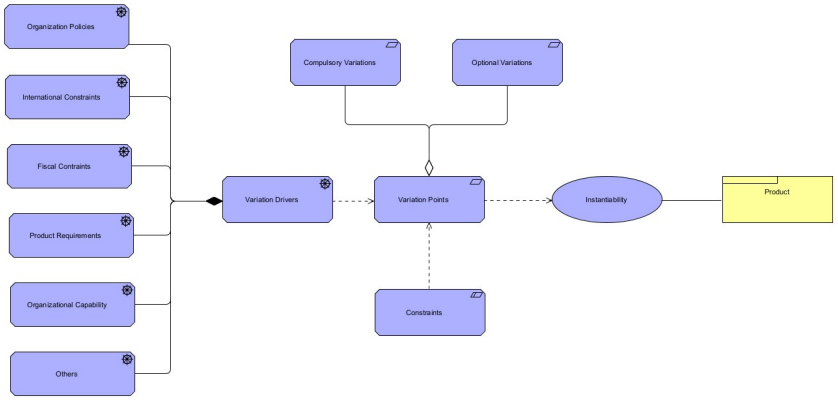

Figure 3: Variability management concepts model

easier as the research can get inspiration from other studies and their approach to evaluation [94].

Nevertheless, evaluation of the RAs is a well-known challenge among researchers [34]; [95]; [96]; [58]. RAs and concrete architectures have distinct qualities. They vary in at least 3 major ways;

1. RAs are of higher level of abstraction
2. in RAs stakeholders are not clearly grouped
3. RAs tend to be focused more on architectural qualities

While there are many well-established methods for assessing concrete architectures such as Scenario-based Architecture Analysis Method [97], Architecture Level Modifiability Analysis [98], Performance Assessment of Software Architecture [99], Architecture Trade-off Analysis Method [100], none of these methods can be directly applied to evaluate RAs. To support this statement, three major issues have been identified. These issues are as follows;

1. One of the main problems for applying existing evaluation methods to RA is the lack of clearly defined group of stakeholders [30], while ATAM and other methods are highly dependent on participation of stakeholders for evaluation. Due to the level of abstractness of the RA, reaching various group of stakeholders and persuade them to anticipate in the study, is

problematic and does not fit to the timeline of this study. Even more notably, it is unlikely that all stakeholders will unite around a common reference architecture as different members may or may not agree with the overall idea of the RAs, may come from different backgrounds, and may lack architectural visions

2. Evaluation frameworks and methods for concrete architectures make use of scenarios. Howbeit due to RAs level of abstraction, creation of usable scenario is difficult. Either a large set of scenarios should be developed covering all the aspects of the RA with regards to specific domain, or a more general scenarios should be developed to cover all the aspects. In the first approach, a large number of scenarios, makes data analysis troublesome and a tedious process. Moreover, the order of prioritization of these scenarios and defining them, and validating them is a problematic task. In the second approach, due to the generality of the scenario, evaluation of effectiveness and usability of the RA becomes difficult and may become incomplete [95]. These challenges have been observed even in the evaluation of highly complex concrete architectures in information systems domain [101].

Based on the problems discussed above, available methods of architecture analysis are not sufficient in evaluating the RA. This has been addressed by various researchers in the industry.

In one study, Angelov et al [30], modified ATAM and extended it to resonate well with RAs. This process took place by invitation of representatives from leading industries for the evaluation process, and the selection of various contexts and defined scenarios for these contexts. Furthermore, ATAM has been extended to evaluate completeness, buildability and applicability. Howbeit the selection of the right candidate and involving them in the process is a time-consuming and daunting task and may yield incomplete information. In addition, candidates maybe lacking architectural visions, increasing the threat to validity.

In addition to extending ATAM for RAs, Graaf et al [102] presented an evaluation approach in which SAAM is extended to help reduce the organizational impact of it. In Another study by Maier et al, Maier et al. (2013) as a post-graduate thesis in Eindhoven University of Technology, the evaluation of the RA has been conducted by mapping it against existing concrete architectures described in industrial whitepapers and reports. Along the lines, Galstar et al [24] suggested reference implementations, prototyping and incremental approach for the validation of the RA.

Rohling et al [103] have evaluated their RA by mapping it against the requirements set for the study. This was facilitated by the RA research methodology created by Nakagawa et al [104] and the complementary RAModel [26].

Inspired by all the studies listed, for the purposes of this study, we will first create a prototype of the RA in an actual organizational setup and then we will use ATAM to evaluate the concrete architecture.

4. Cybermycelium: A Domain Driven Distributed Reference Architecture for Big Data Systems

If our aspiration to enhance every business aspect with data needs to come to fruition, we need a different approach to data architecture. Traditional data warehouse approaches to business intelligence, while have addressed the volume and computing aspect of data, have failed to address other characteristics of it; heterogeneity and proliferation of data sources (variety), the speed at which data arrives and needs to be processed (velocity), the rate at which data mutates (variability), and the truth or quality of the data (veracity).

4.1. State of the art

The available body of knowledge and the knowledge from practice highlight 3 generations of BD architectures;

1. **Enterprise Data Warehouse:** this is perhaps one of the oldest approaches to business intelligence and data crunching and hast existed even

before the term BD was coined [105]. Usually developed as proprietary software, this data architecture pivot on enterprise data warehouse, ETL jobs, and a data visualization software such as Microsoft Power BI. As the data sources and consumers grow, this architecture suffers from hard to main ETL jobs, and visualizations that can be created and understood by a certain group of stakeholders, hindering data's positive impact on business. This also means, new transformations will take longer to be added to the workload, the system is monolithic and hard to scale, and only a few group of hyper-specialized individuals are able to operate the system. Moreover, data warehouses have been designed with different assumptions that cannot effectively handle the characteristics of big data.

2. **Data Lake**: to address the challenges occurred in the first generation of data architectures, a new BD ecosystem emerged. This new ecosystem revolved around a data lake, in a way that there isn't as much transformations on the data, but rather everything is dumped into the data lake and retrieved when necessary. Although data lake architecture have reached a higher level of success in comparison to the first generation of the data architectures, they are still far from optimal. As data consumer and data providers grow, data engineers will be immensely challenged to avoid creation of data swamp [106], and because there is usually no concept of data owner, the whole stack is usually operated by a group of hyper-specialized data engineers, creating silos, and barriers for gradual adoption. This also means various teams will often go into data engineers backlog and will not be in control of how and when they can consume the data they desire. Furthermore, data engineers are usually oblivious of the semantics and value of the data they are processing; they simply do not know how is that data useful or which domain it belongs to. This will overtime decrease the quality of data processing, results in haphazard data management, and make maintenance and data engineering a complicated task.
3. **Cloud Based Solutions:** Given the cost and complexity of running a

data lake on-premise alongside the whole data engineering pipeline, and the substantial talent gap currently faced in the market [6], the third generation of BD architectures tend to revolve around as-a-service or on-demand cloud-based solutions. This generation of architecture tends to be leaning towards stream-processing with architectures such as Kappa or Lambda [107], or frameworks that unify batch and stream processing such as Apache Beam [108] or Databricks [109]. This is usually accompanied by cloud storage such as Amazon S3, and streaming technologies such as Amazon Kinesis. Whereas this generation tends to solve various issues regarding the complexity and cost of data handling and digestion, it still suffers from the same fundamental architectural challenges. It does not have clear data domains, a group of siloed hyper-specialized data engineers are running them, and data storage through a monolithic data pipelines soon becomes a choke-point.

To discuss the integral facets that embroil these architectures, one must look at the characteristics of these architectures and the ways in which they achieve their ends, with quality attributes surrounding it. Except for one case [3], all the architectures and RAs found as the result of this study, were designed underlying monolithic data pipeline architecture with four major components being data consumer, data processing, data infrastructure and data providers.

The process of turning data into actionable insights in these architectures usually follow a similar lifecycle;

1. **Data Ingestion:** system beings to ingest data from all corners of the enterprise, including both transactional, operational and external data. For instance, in a practice management software for veterinaries, data platform can ingest and persist transactional data such as 'user interaction with therapeutics', 'number of animals diagnosed', or 'number of invoices created' and 'medicines dispensed'.
2. **Data Transformation:** data captured from the previous step is then cleansed for duplication, quality, and potentially scrubbed for privacy poli-

cies. This data then goes through a multifaceted enrichment process to facilitate data analysis. For instance, a journey of the veterinary nurse can be captured at every stage, enriched with demographics and animal breed for regression analysis and aggregate views.

3. **Data Serving:** at this stage, data is ready to be served to diverse array of needs ranging from machine learning to marketing analytics, to business intelligence to product analysis and customer journey optimization. In the 'veterinary practice management software' the data platform can provide real-time data through event backbone system such as Kafka about customers who have applied and have been dispensed Restricted Veterinary Medicine (RVM) to make sure that these transactions comply with the conditions of the registration of these products.

The lifecycle depicted is indeed a high-level abstract view of prevalent BD systems. Howbeit, it highlights an important matter; these systems are all operating underlying monolithic data pipeline architecture that tends to account for all sorts of data. This means, data that logically belong to different domains are now all lumped together and crunched in one architectural constructs, making maintainability and scalability a daunting task [110].

While architectures in software engineering have gone through series of evolution in the industry, adopting a more decentralized and distributed approaches such as microservice architecture, event driven architectures, reactive systems, and domain driven design [111], the data engineering, and in specific BD ecosystems do not seem to be adopting many of these patterns. Evidence collected from this study have proven that attention to decentralized BD systems, metadata, and privacy is deficient. Therefore, the whole idea of 'monolithic data pipeline architecture with no clearly defined domains and ownership' brings significant challenges to design, implementation, maintenance and scaling of BD systems.

Suppose company A would want to adopt a BD initiative to embark on this complex endeavour, what would be the first step ? does the company have to

worry about high-throughput stream processing ? does it have to worry about regional privacy regulations? does it have to worry about cost-efficient batch processing? perhaps yes to all of these questions, but what's even more integral to the success of the whole endeavour is the underlying architecture that governs the entire system, its components, their relations to each other, data flow and principles and standards that govern the quality attributes and evolution of the system.

This architecture and design process if done underlying current prevalent approaches, can bring about colossal losses, and leave many managers disappointed. Nevertheless, we don't claim that all these architectures will fail, perhaps some have proven to be successful in a specific context. There are two threats to maintainability and scalability of these systems;

1. **Data source proliferation:** as the BD system grows and more data sources are added, the ability to ingest, process, and harmonize all these data in one place diminishes. This in turn, reduces maintainability, makes company reliant on lead data engineers who built the infrastructure, and makes scaling these systems very difficult. The proliferation of data sources if not managed carefully, can result in data swamps as well, which makes understanding data domains, and providing data as a service a complicated task.
2. **Data consumer proliferation:** organizations that utilize rapid experimentation approaches such Hypothesis-Driven Development and Continuos Delivery [112] constantly introduce new use cases for data to be consumed in different domains. This means that variability of the data rises, and the sum of aggregations, projections, and slices increases, which in turn adds more work to the backlog of the data engineering team, slowing down the process of serving the data to consumers. Inability to account for the data consumer demands can be a point of friction in organizations [110].

To address these challenges, the lead architect or the architecture governance

group will then have to choose the right architectural quanta to segregate the monolith. According to Ford et al [113], an architectural quantum is a component of a system with high functional cohesion that is independently deployable, this is also referred to as a service [114]. The main motivation for segregating the monolith into its architectural quantum, is to parallelize work in various business domain, to reach a better velocity, reduce cost, promote ownership, increase performance and reach higher operational scalability.

Currently, these architectures are usually segregated into pipelines that each process data differently. While each pipeline has its own responsibility to handle various aspect of the BD system, there is still a high coupling between the pipelines, as 'data cleansing' phase cannot start after 'data ingestion'. This coupling is even more highlighted when the company is at the stage of rapid experimentation with data sources and would like to explore new domains of insight generation, and this in turn means that delivering new features and values is orthogonal to the axis of change.

Using the same practice management software example, given that a new class of animals (equine animals as opposed to small animals) should be incorporated for data analysis; the data engineering team should then modify and extend the whole pipeline of ingest, process and serve to account for the particularity of the data captured regarding this new class of animals. New ingestion services required, the schema might change, the veracity checking mechanisms might differ, cleansing varies and more. This implies an end-to-end dependency which affects external teams, slows down processes and make maintenance gradually harder. This implies that using pipeline as an architectural quantum in such a coupled way is perhaps not the most efficient architecture to BD systems.

Another major issue with the current architectural approaches is that data engineering is usually confined into a team of hyper-specialized individuals who are siloed from the operational units of the organization. These teams, being fully responsible for creating the infrastructure for data processing, are often absent of business knowledge and the domain, which limits their productivity. These individual usually have a limited understanding of the data sources, data

provenance, data consumers, the changing nature of the business domains, the overall product vision, and the application side of things, yet they are responsible to provide data for a large array of analytical and operational needs in a timely manner. For instance, given a context in which a product owner and application developer can cooperate, the synergy between the data engineer, application developer, and product owner can bring about more mature decisions that can align the requirements across various technical and logical domains and allow for various stakeholders to contend and communicate their concerns.

Whereas there could be other factors to be discussed deeply in this paper regarding current BD architectures, our aim is not to explore any further and emphasize more on the solution artefact we've designed to address some of these challenges.

5. A paradigm shift: distributed domain driven architecture

Based on the premises discussed priori to this section, one can infer that the idea of monolithic and centralized data pipelines that are highly couped and operated by silos of hyper-specialized BD engineers has limitations and can bring organizations into a bottleneck .

We therefore, explore a domain driven distributed and decentralized architecture for BD systems and posit that this architecture can address some of the challenges discussed. This idea is inspired by the advancements in software engineering architecture, and in specific event-driven microservice architecture [115], domain driven design [116], and reactive systems [117].

Data usually comes into two different flavours; 1) operational data which serves the need of an application, facilitates logic, and can include transactional data and 2) analytical data which usually has the temporality to it, and is aggregated to provide with insights.

These two different flavours, despite being related, have different characteristics and trying to lump them together may result in a morass. To this end, Cybermycelium realizes the varying nature between these two planes and re-

spects the difference. Cybermycelium aims to transfigure current architectural approaches by proposing an inversion of control, and a topology based on product domains and not the technology [118]. Our proposition is that handling two different archetypes of data, should not necessarily result in siloed teams, heavy backlogs, and a coupled implementation.

To further elucidate on this matter, we take the example of the microservice architecture. As the industry sailed away from the monolithic n-tier architectures into Service Oriented Architectures (SOA), organizations faced a lot of challenges. One prevalent issue was around the maintenances of Enterprise Service Bus (ESB) or SOA bus, which is the locus of aggregation. While the aggregation layer could be written very thin, the reality is that the transformation of XML and logical operations started to bloat the SOA bus. This added a new level of coupling between internal and external elements of the system as a whole [119]; [120]; [121].

Microservices architecture, being the evolution of SOA, move away from smart pipelines into dumb pipelines and smart services removing the need for the locus of aggregation and control. Moreover, there was no business logic written in the pipelines, and each service was segregated usually with the help of domain driven design.

Whereas microservices architecture still have its challenges, the gradations of software architectures in software engineering industry can be analogous to the data engineering domain. One can perceive the pipeline architecture and its coupling nature similar to SOA and the business logic written to connect the services in the SOA bus.

Based on these premises we posit 4 underpinning principles for Cybermycelium;

1. Distributed Domain driven services with bounded context
2. Data as a service
3. Data infrastructure automation
4. Governance through a federation service
5. Event driven services

5.1. Distributed Domain driven services with bounded context

Integral to Cybermycelium, is the distribution and decentralization of services into domains that have clear bounded context. Perhaps one the most challenging things one might face when it comes to architecting a distributed system is; based on what architectural quanta should we break down the system. This issue has been repeatedly discussed for example among adopters of microservices architecture . Cybermycelium, inspired by the concept of domain-drive design, tends to sit data close to the product domain that relates to it. This implies that data inheres in the product domain and as a facet of it [46].

This is mainly driven by the fact that most organizations today are decomposed based on their products. These products are the capability of the business that are segregated into various domains. Domain's bounded context is operated by various teams with different visions and concerns, incorporating data into a bounded context can result in a synergy that can improve the management of evolution and continuos change. This can be micro, such as application developers communicating with data engineers about collecting user data in a nested data structures or in flat ones, or macro, such as application developers thinking about redesigning their graphql schema in an intermediary layer that may affect the data engineers ingestion services.

5.2. Data as a service:

Data can be conceived as the fourth dimension of a product next to UI/UX, business and application (5.2). Each domain provides its data as a service. This data is consisting of both operational and analytical data. This also implies that any friction and coupling between data is removed. For instance, the 'invoice' domain will provide the transactional data about number of invoices and total of discounts with analytical data such as which practices have created what number of invoices in what period of time.

However this data-as-a-service model should be carefully implemented to account for explorability, discoverability, security, and quality. The data provided as a service should have the identical qualities to customer-facing products. This

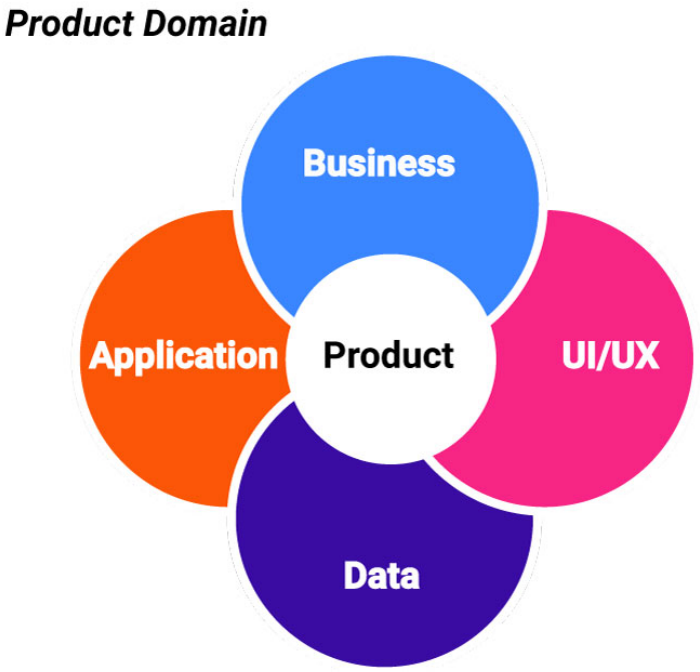

Figure 4: Product Facets

also implies, that a product owner should now treat data facet as an aspect of the product and employ objective measures that assure the desired quality. These measure can be net promoter scores from data consumers, data provenance, and decreased lead time. Product owners, in addition to the application and design aspect of the product, must now incorporate this new facet, and try to understand the needs of the data consumers, how they consume the data, and what are the common tools and technologies they utilized to consume the data. This knowledge can help shaping better interfaces for the product.

Product domains may also need to ingest data from upstream domains, and this requires the definition of clear interfaces. Furthermore, each domain should also account for metadata. Metadata in derived from the nature of the product and its data lifecycle. Data can be ingested and served in various forms such as tables, graphs, JSON, events, and many more; but in order for the data

to be useful for analytical purposes, there is a need to associate data with its corresponding metadata that encompasses semantics, and history.

5.3. Data infrastructure automation

As the number of product domain increases, the effort required to build, deploy, execute, and monitor services increases. This includes the data pipelines required for that product domain to carry out its functions. The platform skills required for these kinds of work is usually found in Devops engineers and site reliability engineers. Application developers and data engineers are usually not adept at carrying out such workloads in an efficient manner. For this reason, there is a need for highly abstract reusable infrastructural components that can be easily utilized. This implies that teams should be equipped with required infrastructure as a service, that can be easily employed to account for BD needs.

One way to provision such infrastructure as a service, is to utilize infrastructure as a code software tools like Terraform [122]. Besides, data infrastructure may be extended based on currently running infrastructure for application payloads. However, this might be challenging, as the BD ecosystem is growing rapidly, and while a software application might be running in an EC2 worker node in an EKS cluster on Amazon, the BD system maybe running Databricks, or a CDP solution like Segment [123], HDFS [124], or Amazon Kinesis.This brings the challenge of composing data and application infrastructure together to provide with coherent, cost efficient interoperable infrastructure.

Nevertheless, this should not be a daunting task, as one can simply extend the worker nodes map in the EKS code written for Terraform to add a new node in the network, which installs Databricks through a Helm Chart [125]. In addition, the data infrastructure should be accompanied with proper tooling. Tools like GNU Make [126], makes it quite easy for developers and data engineers to deploy infrastructure as they demand. A mature infrastructure as a service should provide the team with core infrastructures such as BD storage, stream processing services, batch processing services, event backbones or message queues, and data integration technologies.

5.4. Governance through a federation service

The other principle of Cybermycelium is the global governance or the global standardization of the services. This principle is perhaps a lesson learnt from the studied application of Miroservices architecture in the industry [111]. Distributed architectures are made up of independent collection of nodes, with distinct lifecycle that are deployed separately and are owned by various teams. As the number of these services grow, and the interconnections increase, the challenge of maintaining and scaling the system increases. This means services need to interoperate, provide services, ingest data from other services, perform graph or set operations in a timely manner and do stream processing.

In order to scale and maintain these independently deployed yet interconnected services, Cybermycelium needs a governance model that embrace domain autonomy, distribution and decentralization, automation and Devops, and increased interoperability through federated government. This requires a shift in thinking, which obsoletes many prevalent assumptions of software and data engineering. The point of federation is not to suppress or kill the creativity and innovation of the teams, but rather, introduction of global contracts and standards that are in-line with company's resources and vision. This therefore can be a challenging task for software architects to find the equilibrium bet ween right amount of centralization and decentralization. For instance, semantic related metadata can be left to the product domain to decide, whereas policies and standards for metadata collection should be global. This is somewhat analogous to architectural principles in TOGAF's ADM [127].

The definition of these standards is up to the architecture, or architectural governance group, and is usually achieved through service level objectives (SLOs) or well-defined contracts and standards.

5.5. Event driven services

Cybermycelium has been designed in a decentralized and distributed manner. Despite the advantages of decentralized systems in terms of maintenances and scalability, communication between the services remains a challenge. As

the number of services grow, the communication channels increases, and this soon turns into a nexus of interconnected services that each try to meet its own end. Each service will need to learn about the other services, their interfaces, and how the messages will be processed. This increases the coupling between services and makes maintenance a challenging task. We argue that this should not be the aim of a distributed RA such as Cybermycelium.

One approach to alleviate these issues is asynchronous communication between services through events. This is a different paradigm to a typical REST style of communication. A point-to-point communication occurs between services as series of 'command', like getting or updating a certain resources, whereas event-driven communication happens as a series of events. This implies that instead of service A commanding service B for certain computation, service B reacts to a change of state through an event, without needing to know about service A.

This provides a 'dispatch and forget' kind of a model, in which a service is only responsible to dispatch an event to a topic of interest for the desired computation. In this way, the service does not need to wait for the response and see what happens after the event is dispatched, and is only responsible for dispatching events through a well-defined contract. Underlying this paradigm, services do not need to know about each other, but rather they need to know what 'topic' they are interested in.

This is analogous to a kitchen, where instead of a waiter needing to communicate directly to another waiter and to the chef and to the cook, they all react to certain events, such as customers coming in, or an order slip being left on a counter. The subtlety lies in the underlying paradigm and philosophy of 'event' instead of 'command'. This paradigm solves many issues of communication in distributed BD systems such as long running blocking tasks, throughput, maintenance, scale and ripple effect of service failure.

It is worth mentioning, that eventual consistency (BASE) is preferred over ACID transactions for performance and scalability reasons. The detail of these two varying kind of transactions is outside the scope of this study.

5.6. The Artefact:

After having discussed many kernel and design theories, the necessary theoretical foundation is created for the design and development of the artefact. Cybermycelium is created with Archimate and displays the RA mostly in technology later. Displaying these services in technology layer means that it's up to the designer to decide what flow and application should exist in each node. For the sake of completion, and as every software is designed to account for a business need, we have assumed a very simple BD business process. While this business layer could vary in different context, Cybermycelium should be able to have the elasticity required to account for various business models. To ease understanding of the RA, we sub-diagrammed in product domain (6).

Cybermycelium is made up of 11 main components and 9 variable components as depicted in figure 5.

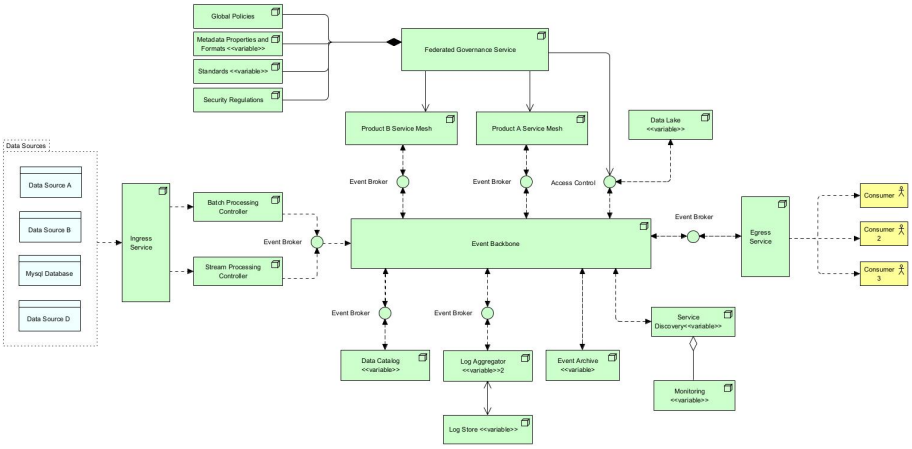

Figure 5: Cybermycelium BD Reference Architecture

For the purposes of effective modeling and abstraction, we've sub-diagrammed the product domain, which is portrayed in figure 6

The main elements are;

1. **Ingress Service:** The ingress service is responsible for exposing the necessary port and endpoint for the data to flow to the system. Depending

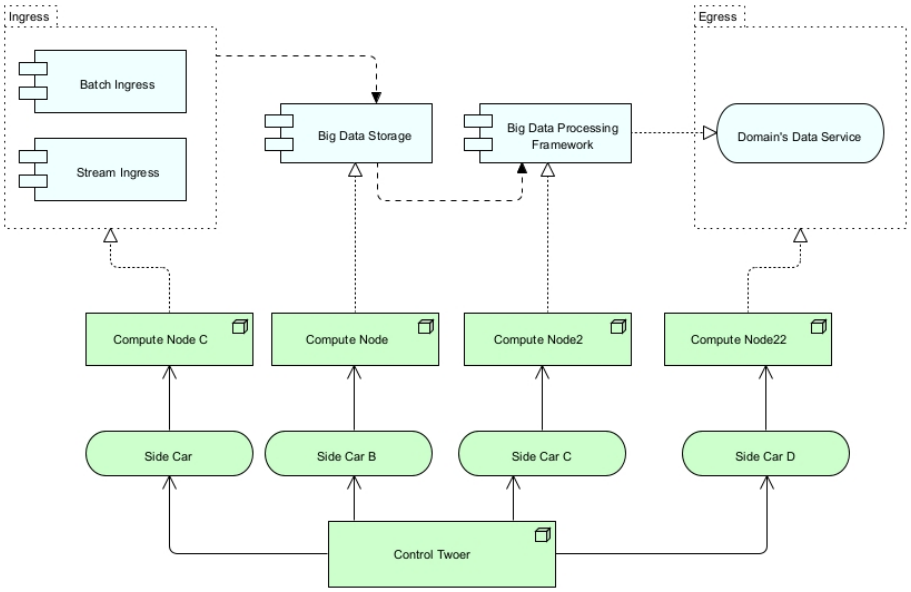

Figure 6: Cybermycelium Product Domain Design

on the nature of the request, the ingress service will load balance to either batch processing controller or stream processing controller. It is essential for the ingress service to operate asynchronously to avoid any potential choke points. In addition, ingress handles the SSL termination, and potentially name-based virtual hosting. Ingress has several benefits. Firstly, it helps with security by preventing port proliferation and direct access to services. Secondly, it help with performance by distributing requests based on their nature, and SSL termination. Thirdly, if there's a need for object mutation through a proxy, ingress is the best architectural construct. Having an ingress also means that the point of entry is clear, which makes monitoring easier, and allows for other components of the architecture to remain in private networks.

2. **Batch Processing Controller:** Batch processing controller is responsible for dispatching batch events to the event backbone. This service should be a small service (could be a Lambda) with the main responsibility of receiving a request for batch processing and dispatching an event to the

event broker. Because the nature of the request is of type batch and has been clearly distinguished by the ingress, batch processing controller can dispatch events in bulk and asynchronously. This is the main difference of this service to stream processing controller. Batch processing controller can execute other non compute-intensive tasks such as scrubbing properties from the given data or adding headers. Having a specific controller for batch processing improves monitoring and allows for customized batch event producing.

3. **Stream Processing Controller:** Stream processing controller is responsible for dispatching streaming events to the event backbone through the event broker. This service has been segregated from the batch service as it has to account for a different nature of events. Streams are synchronous in nature, and can require high-throughput. This service is a small service as well, but non-heavy computations such as enabling stream provenance, and one-pass algorithms can be utilized. Having a specific controller for streaming processing means that custom attributes can be associated to stream events, and the events can potentially be treated differently based on the nature of the system. This also eases monitoring and discovery.
4. **Event Broker:** Event brokers are designed to achieve 'inversion of control'. As the company evolves and requirements emerge, the number of nodes or services increases, new regions of operations may be added, and new events might need to be dispatched. As each service has to communicate with the rest through the event backbone, each service will be required to implement it's own event handling module. This can easily turn into a spaghetti of incompatible implementations by various teams, and can even cause bugs and unexpected behaviors. To overcome this challenge, an event broker is introduced to each service of the architecture. Each service connects to its local event broker and publishes and subscribes to events through that broker. One of the key success criteria of the event broker is a unified interface that sits at a right level of abstraction to account for all services of the architecture. Event brokers, being

environmentally agnostic can be deployed to any on-premise, private or public infrastructure. This frees up engineers from having to think about the event interface they have to implement and how it should behave. Event brokers can also account for more dynamism by learning which events should be routed to which consumer applications. Moreover, event brokers do also implement circuit breaking, which means if the service they have to broke to is not available and does not respond for a certain amount of time, the broker establishes unavailability of the service to the rest of the services, so no further requests come through. This is essential to preventing a ripple effect over the whole system if one system fails.

5. **Event Backbone:** This is the heart of the Cybermycelium, facilitating communication among all the nodes. Event backbone in itself should be distributed and ideally clustered to account for the ever-increasing scale of the system. Communication occurs as choreographed events from services analogous to a dance troupe. In a dance troupe, the members respond to the rhythm of the music by moving according to their specific roles. In here, each service (dancer) listens and reacts to the event backbone (music) and takes the required action. This means services are only responsible for dispatching events in a 'dispatch and forget' model, and subscribe to the topics that are necessary to achieve their ends. Event backbone thus ensures a continues flow of data among services so that all systems are in the correct state at all times. Event backbone can be used to mixed several stream of events, caching of events, archiving of events, and other manipulation of events, so long as it's not too smart! or does not become a ESB of SOA architectures. Ideally, an architect should perceive the event backbone as series of coherent nodes that aim to handle various topics of interest. Over the time, event backbone can be monitored for access patterns and facilitate the communication at a faster rate.
6. **Egress Service:** The egress service is responsible for providing necessary APIs for the consumers of the system to request data in demand. This is a self-serve data model in which data scientists or business analyst can

readily request data from various domains based on the data catalogue. Clients can first request for a data catalogue and then use the catalogue to request for the product domain that accounts for the desired data. This request can include several data products. Egress is responsible to route the request to the data catalogue, and to corresponding product service mesh' in order to resolve values. The egress realizes the address to service meshes and other services through the data catalog and service discovery. The egress service should cache the resolved addresses and values in order to increase performance and response time. An architect can even choose the implement a complete query cache component inside the egress service, however that will make maintenance potentially more difficult and may result in bottlenecks. This is to avoid having people requesting directly to data engineers for various big data requirements, and means that people can just request for what data they need, analogous to a person who orders food at a restaurant, menu being the data catalog, and egress being the waiter.

7. **Product Domain Service Mesh:** As previously discussed a product is a capability of the business, and each product has its own domain consisting of the bounded context and the ubiquitous language. In system and architectural terms, these domains are implemented as a service mesh. Each service mesh is made up of a batch ingress, stream ingress, big data storage, big data processing framework, domain's data service, the required compute nodes to run these services, a side car per service and a control tower. These components provide the necessary means for the domain to achieve its ends. This architectural component removes the coupling between the teams and promotes team autonomy. This means people across various teams are enhanced with the desired computational nodes and tools necessary, and can operate with autonomy and scale without having to be negatively affected by other teams or having friction with platform teams or siloed data engineering teams.
8. **Federated Governance Service:** Evidently, Cybermycelium is a dis-

tributed architecture that encompasses variety of independent services with independent lifecycle that are built and deployed by independent teams. Whereas teams have their autonomy established, in order to avoid haphazard, out-of-control and conflicting relations, there should be a global federated governance that aims to standardize these services. This will facilitate the interoperability between services, communication, aggregates, and even allows for a smoother exchange of members across teams. This also means the most experienced people at a company such as technical leads and lead architects will prevent potential pitfalls that more novice engineers may fall into. However the aim of this service is not centralize control in anyway, as that would be going a step backward into the data warehouse era. The aim of this service is to allow autonomous flow in the river of standards and policies that tend to protect company from external harm. For instance, failing to comply to GDPR while operating in europe can sets forth fines up to 10 million euros, and this may not be something that novice data engineers or application developers are fully aware of. The real challenge of the governance team is then to figure out the necessary abstraction of the standards to the governance layer and the level of autonomy given to the teams. The federated governance service is made up of various components such as global policies, metadata elements and formats, standards and security regulations. These components are briefly discussed below;

(a) **Global Policies:**: general policy that govern's the organizational practice. This could be influenced by internal and external factors. For instance, complying to GDPR could be a company's policy and should be governed through the federated governance service.

(b) **Metadata Properties and Formats:**: this is an overarching metadata standard defining the required elements that should be captured as metadata by any service within the organization, the shape of and the properties surrounding it. For instance, the governance team may decide that each geographic metadata should conform to ISO

19115-1 [128].

(c) **Standards:** overall standards for APIs (for instance Open API), versioning (for instance SemVer), interpolation, documentation (for instance Swagger), data formats, languages supported, tools supported, technologies that are accepted and others.

(d) **Security Regulations:** company wide regulations on what's considered secured, what softwares are allowed, how interfaces should be conducted and how the data should be secured. For instance, company may choose to alleviate risks associated with OWASP top 10 application security risks.

9. **Data Catalog:** As the products increases , more data become available to be served to consumers, interoperability increases, and maintenance becomes more challenging. If then, there is no automatic way for various teams to have access to the data they desire, a rather coupled and slow BD culture will evolve. To avoid these challenges and to in crease discoverability, collaboration, and guided navigation, the service data catalog should be implemented. Data catalog has been listed as a must-have by Gartner [129] and introduces better communication dynamics, easier data serve by services and intelligent collaboration between services.

10. **Logging Aggregator and Log Store:** If all services employ the idea of localized logging, and simply generate and store logs in their own respective environments, debugging, issue finding and maintenance can become a challenging task. This is due to the distributed nature of Cybermycelium and the requirements to trace transactions among several services. In order to overcome this challenge, we've employed the log aggregator pattern popularized by Chris Richardson [130]. The log aggregator service is responsible for retrieving logging events through the event broker from individual services and write the collected data into the log store. The log aggregator configuration and semantics is up to the designer and architecture team. This allows for a distributed tracing, and graceful scaling of organizational logging strategies.

11. **Event Archive:** As the quantity of services grow, the topics in event backbone increases, and the number of events surges. Along the lines of these events, there could be a failure, resulting in timeout and a loss of series of events. This brings system in a wrong state and can have detrimental ripple effect on all services. Cybermycelium tends to handle these failures by using an event archive. The event archive as the name states, is responsible for registering events, so they can be retrieved in the time of failure. If there was a blackout in certain geographical location and the event backbone went down, the backbone can recover itself and bring back the right state of the system by reading the events from the event archive. Th event broker is responsible for circuit breaking, so the service do not request any more events to the backbone while its down. The time to expiry, and what events should be archived is decided based on context in which Cybermycelium is implemented.
12. **Data Lake:** Whereas Cybermycelium is a great advocate of decentralized and distributed systems, we do not find it necessary for each product domain to have it's own kind of a data lake or data storage. This is to prevent duplication, contrasting data storage approaches, decreased operability among services and lack of unified raw data storage mechanisms. Data lake has been designed to store large volume of data in raw format before it can get accessed for analytics and other purposes. This means data can be first stored in the data lake with corresponding domain ownership before it needs to be accessed and consumed by various services. Structured, semi-structured, unstructured and psudo-structured data can be stored in data lake before it gets retrieved for batch and stream processing. Nevertheless, this does not imply that all data should directly go to the data lake; the flow of data is determined based on the particularities of the context in which the system is embodied. One approach that we find suitable is for each team to own a unit of storage in the data lake, which is handled by the access control as depicted on the model.
13. **Service Discovery:** In a distributed setup like Cybermycelium, how do

services discover the location of other services? This is achieved through service discovery. As the practice of hard-coding service addresses in configuration files is not a maintainable or scalable approach, one has to think about an automated scalable solution in which services can become discoverable by other services. The service discovery node is responsible for this job. This is achieved through services registering themselves to the service discovery node when they boot up. Service discovery then ensures that it keeps an accurate list of services in the system, and provides the API necessary for others to learn about the services. For instance, it's idiomatic for an engineer to specify a command to be executed when a Docker container starts (*Node server.js*); thus one can imagine extending the boot up instructions to achieve the registration to the service discovery node. This somewhat resembles to DHCPs and house wifi networks.

14. **Monitoring:** Monitoring systems are integral to robustness of highly dynamic ecosystem of distributed systems and directly affect metrics such as mean time to resolution (MTTR). Services emit colossal amounts of multi dimensional telemetry data that covers a vast spectrum of platform and operating system metrics. Having these telemetry data captured, handled and visualized, helps systems engineers, software reliability engineers, and architects proactively address upcoming issues. Based on these premises, the main responsibility of this service is to capture and provide telemtry data from other service to increase the overall awareness of the Cybermycelium ecosystem. This service is tightly aggregated with the service discovery.

The variable elements in Cybermycelium can be adjusted, modified and even omitted based on the architect's decision and the particularities of the context. The aim of this RA is not limit the creativity of data architect, but to facilitate their decision making process, through introduction of well-known patterns and best practices from different school of thoughts.

6. Evaluation:

Of particular importance to development of a RA, is the evaluation of it. As discussed earlier, we aim to evaluate the correctness and utility of the RA by how it can be turned into an effective context-specific concrete architecture, following the guidelines of ATAM. The main goal of ATAM is to appraise the architectural decisions and thei consequences in light of quality attributes. This method ensures that the architecture is under the right trajectory and in-line with the context. Architecture is a an amalagamation of risks, tradeoffs, and sensitivity points. ATAM shed lights on these matters and highlight potential tradeoff points and risks in a cost-efficient and effective manner.

For ATAM to be successful there should not be a precise mathematical analysis of system's quality attributes, but rather trends should be identified where architectural patterns are correlated with a quality attribute of interest.

For brevity purposes, we do not expand on what ATAM is, and the details of each steps in it, and we only explain how the evaluation has been conducted through ATAM.

This evaluation is consitutent of two phases; phase 1 includes collection of basic information about the company's background, the nature of the practices, and key stakeholders, and phase 2 includes evaluation and analysis of the proposed concrete architecture in the company with clear attention to quality attributes, tradeoffs and risks. Some details are omitted to protect the security and intelectual property of the practice, and some details are modified for academic purposes. These changes have not affected the integrity of evaluation or results depicted in this study.

6.1. Phase 1:

This evaulation is undertaken in a subsidiary of a large-scale international company that has over 6000 employees all around the globe. The subsidiary company offers a pratice management software for veterinary practitioners via Software as a Service (Saas) and has over 15,000 customers from the USA,

UK, Australia, New Zealand, Canada, Singapore and Ireland, among which are some of the biggest equine hospitals, universities and veterinary pracices. The company is currently at the stage of shifting from centralized synchronous architecture into decentralised event driven microservices architecture, and is ambitions to adopt artificial inteligence and BD.

The initial step was the identification ot relevant stakeholders. For this purpose we have approached the key stakeholders in the company's technical governance team. Our aim was to incorporate at least two lead architects of the company in this process. We emphasized on architects that have been with business for a long period of time. This was to ensure that we do not miss any important element in our instantiation. In addition, we made sure that these architects do deeply understand the business and the focal matters sorrounding it. We opted not to include stakeholders that do not directly correlate with software architecture and particularities of it such as UI/UX designers, QA engineers and developers.

During the initial meeting, ATAM has been introduced to the stakeholders. We then described Cybermycelium, our fundamental assumptions, and the variability points. In the second half of the meeting, the stakeholders discussed the history of business, the integral components of it, the current state of the organizations and the business casese they considered suitable for this instantiation. We have then unanimously nominated a few business case that are the most important and relevant to the purposes of this study. This process had more of a discussion nature to it, as the stakeholders have been discussing what would be the best scenario for the case of this evaluation.

6.2. Phase 2:

After having understood the business cases and selecting a few good cases for BD processing, we created an archetype of Cybermycelium. For this purposes, ISO/IEC 25000 SQuaRE standard (Software Product Quality Requirements and Evaluation) [131] was used as a reference for quality technology selection. We did not fully adopt this standard, but was rather inspired by it to make a

better decision. The quality model in the standard is based on characteristics, sub-characteristics and standards. This standard also references many other standards for maintenance and quality keeping of computer systems. The detailed explanation of the standards and its constituent elements are outside the scope of this study.

By applying standard and the requirements of Cybermycelium to the pool of available tools in the industry, we succesfully created the archetype. We chose the tools are the mostly adopted and do support the architectural requirements of Cybermycelium. We did not want to develop tools from scratch, as that would delay our evaluation artefact and this would affect the stakehodlers negatively. In addition, many mature tools exist that statisfy our architectural requirements, so therefore 'reinventing the wheel' was unnecessary.

It is also worth mentioning that the archetype is not a full instantiation of the Cybermycelium, but rather a partial instantiation based on given business cases. The concrete architecture created out of Cybermycelium for the archetype is depicted in figure 7

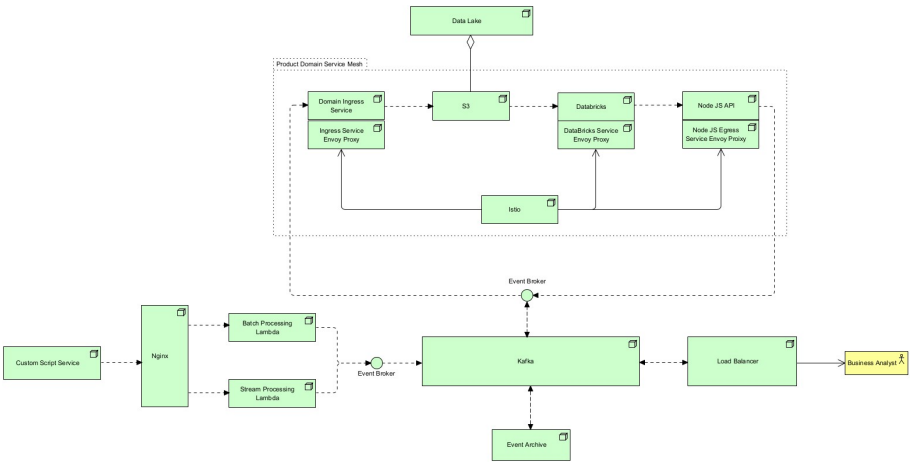

Figure 7: Cybermycelium Instantiation

For the purposes of this archetype we've written a custom script that extracts data out of mySQL and then send it to Cybermycelium. Whereas there could

be a service written in a product domain service mesh to directly connect to mySql to get values, we decided to have this proxy server, firstly because of company's security and privacy concerns, and secondly, because we wanted to create a flow that respects the architectural integrity of Cybermycelium.

As for the technology choices, we chose Node JS for all the APIs, and custom scriptings, Nginx as our ingress, AWS Lambdas for stream and batch processing controllrs, Kafka for the event backbone, Kafka event Brokers as the event broker, AWS Application Load Balancer as the egress load balancer (business analysts directly send an API request to the load balancer URL), Istio as the control tower, Envoy as the side car, Kubernetes as the service mesh enabler and container orchestration, Node JS Fastify web framework as the domain ingress service, AWS S3 as the BD store (We used AWS data lake, which internally uses S3) and event archive, Data Bricks for stream and batch processing, and another Node JS Fastify instance for providing the domain data as a service.

After this step, we presented the archetype to the stakeholders, discussed architectural approaches, discusses our choices of technology, highlighted quality attributes and prioritized business scenarios.

6.2.1. Identifying Architectural Approaches:

To establish the architectural styles, we first analyzed the archetypes with respect to key quality attributes chosen for this evaluation which are performance, availability and modifiability.

- For performance, Nginx, Kafka, Istio, DataBricks and the AWS Application Load Balancer have been described.
- For availability, Kafka, Event archive, Nginx, controllers, Data Lake and Istio have been discussed.
- For modifiability, the concept of domain driven design, the service mesh, zere coupling, the plug and play nature of the archetype, the ability to add desireable services through event brokers, and the distributed nature of the architecture has been discussed.

We then proved each of the quality attributes for potential risks, tradeoffs, and sensitivty/variability points.

6.2.2. Scenario Prioritisation:

Scenarios are the quantum of ATAM, and help captring stimuli to which the architecture has to react. These stimuli help to highlight system's ability to too meet desired functional and non-functioanl requirements [100]. Based on this premise, in this step, we asked stakeholders to come up with three different kind of scenarios namely growth scenarios (anticipated changes), use-case scenarios (typical usage of the system) and exploratory scenarios (extreme cases). The result of this created 20 scenarios, which we then asked stakeholders to vote on. The result of the voting yielded 5 scenarios which are described as two user journeys;

- A cat owner brings a cat to the veterinary hospital. The cat has symptoms of a lyme disease, and should be diagnosed in a timely manner to avoid master problems.
- There has been numerous cases of cancer in pets in certain environments. This environment should be analyzed to see if environmental factors play a cancer inducing role.

6.3. Utility Tree Elicitation:

In order to generate the utility tree, first we had to learn what are the most important quality attributes. We first presented our key quality attributes that we have assumed to be important, and double-checcked it with the stakeholders. Whereas some stakeholders raised concerns over privacy, the members unanimously agreed that performance, availability, and maintainability are the most important quality attributes. This was in-line with our assumptions. Based on these premises, the utility tree has been generated 8.

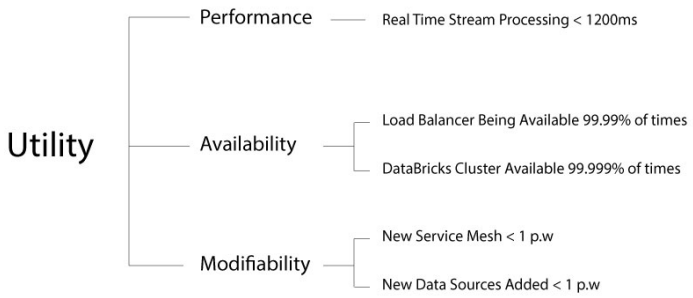

Figure 8: Utility Tree

6.3.1. Analyze Architectural Approaches:

After having scenarios prioritised and architectural approaches identified, it's time to analyze if the architectural approaches are the fitting for the given scenarios by the means of simulating those scenarios against the system. This is to provide heuristic qualitative analysis, and highlight tradeoffs, risks, and sensitivity points.

Therefore, we emulated the scenarios against the archetype by creating relevant topics in the Kafka, having the data flow, having the ingress in the service mesh digest it and flow it into the storage and processing and so on so forth. We've been using real world data, so there was no need for data fabrication and synthesis. We configured Nginx to pass the request to the responsible Lambdas, and Lambdas then produced the necessary events and sent it to Kafka.

In the process of running simulation scenarios against our concrete system, we probed our architectural approaches, which led to emergence of several questions;

- How does the system reocover if the event backbone goes out of order?
- What if the service mesh ingress is not available?

- Should privacy be it's own service? or should it sit in federation ?
- Should have a dedicated service mesh for metadata management?
- How easy it is to extend and modify current services?
- Should there be a certain order to events ?
- Is there a benefit in creating event mesh between event brokers?
- Where is the best place to scrub sensitive data from the incoming streams?

It is essential to realize that the RA is at a higher level of abstraction, aiming to capture the best architectural solutions for a class of systems, while the prototype of it help arising many details, screening questions, tradeoff points, sensitivity points, and organizational matters. Tradeoff points is defined as the point in which service can affect various quality attributes. These points are of high importance as they can drastically affect the overall behaviour of the system.

Based on these premises, stakeholders feedback, utility tree, and the architectural qualities of Cybermycelium, we deduce that system quality Q_S, is a function f of the quality attributes availability Q_A, performance Q_P, and modifiability Q_M.

$$Q_S = f(Q_M, Q_A, Q_P) \tag{1}$$

6.3.2. Performance:

In order to analyze our approach in-line with the utility tree, after having created the simulated scenarios, we used a cloud stress testing testing agent (StressStimulus). After having run this stess test a couple of times, it has become evident to us that cold start times latency of AWS Lambda services can affect the performance requirements stated in the utility tree. A Lambda can take anywhere from 100ms to over a second on cold start time. This latency varies and hard to nail down, but even considering the latency, we have captured

an average of 1000ms response time from our system which is inline with the utility tree. While replacing Lambdas with EC2s or Fargates could solve this issue, it would increase the cost, affect the maintainbility of the architecture (a server has to be provisioned and maintained), and would require rework of several services.

In addition, other Lambda like solutions exist that have actually sovled the cold start problem; one good example is cloud workers offered by CloudFlare. However the company chosen for the purposes of this evaluation is not yet open to a multi-cloud approach, and thus AWS is the only option. Moreover, one could implement predictable start-ups with provisioned concurrency, but that requires more effort and is outside the scope of this study. As our architecture is distributed, we have also measured the latency in between services as tail latency is known issue in distributed systems. Due to the fact that our service mesh was hosted in a private network on a virtual cloud, we could not find any major issue with cloud latency, and our average response time was under 1000ms. Implementing a streaming processing in Databricks, we opted not to use micro-batch to have an accurate evaluation, and we decided not to configure the fair scheduling pool, so as to test the worst case scenario.

After creating and analyzing various performance models of the system, it has come clear to us that latency, and side-effects like input/output, and mutation/transformations were the most important performance sensitivity points. Our performance model were built underlying the following cases;

- Priodic, regular data dispatch to the product domain
- Sending large volume of data (over 200mb) to the system, reaching the throughput threshold
- Sending many request simutaneously through the cloud stress testing tool

The event-driven nature of the system really helped with handling throughput and concurrency. Whereas there has been bottlenecks in the areas of storage and network latency, the system managed to reach desired performance on av-

erage. Given this insight and after some rigorous testing, we characterize the system's performance sensitivity as follows;

$$Q_{\mathrm{P}} = h(s, l, cbp) \tag{2}$$

That is the system is sensitive to latency (l), side effects (s) and concurrency back pressure (cbp).

6.3.3. Availablity:

As guided by the utlity tree, the key stimulus to model for the prototype is the failure of the ingress (load balancer) the data processing cluster and most importantly the event backbone. Due to the distributed nature of Cybermycelium, and the derived prototype, failure in one service, if not handled properly, can have a ripple effect on the system. This is one area, where we found the idea of 'event brokers' really helpful. By implementing circuit breakers in event brokers, we prevented the other nodes of the system to be affected by failure of one. We also archived the events that the node was about to receive before it failed.

Whereas the event archive has played an ancillary role in providing archive to various circuit breakers, it's main functionality was to provide event history to the event backbone in the case of failure. This is again achieved by circuit breaking at the broker level and event retrieval from the event archive. On the other hand, in relation to container orchestration and health check, Kubernetes provided with a declarative API to handle the state of the system. With setting Replica sets, and necessary deployments, the master node kept ensuring that certain number of pods are always available. This implies that it's critical for master node to be available at all times.

Based on these findings, we characterized system's availability as following (g is fraction of time that system is working);

$$Q_{\mathrm{A}} = g(\lambda_{\mathrm{E}}, \mu_{\mathrm{C}}, \mu_{\mathrm{S}}) \tag{3}$$

That is, system availablity is primarily affected by the failure rate of the event backbone (λ_{E}), the time it takes for circuit breaker to trip and become

available again (μ_C), and the time it takes for the service to recover from failure (μ_S).

One major factor that really helped alleviating many issues of the distributed systems, was the cloud-native aspect of Cybermycelium. Whereas this aspect of the architect has not beed discussed previously, the prototype was easily deployed in AWS with well-known devices. As we did not handle on-premise data centers, many of the hardware was handled by the cloud company.

6.3.4. Modifiability:

To analyze modifiability, we followed the guidelines of SAAM [97]. The distributed and service driven nature of the prototype allowed us to easily achieve the utility tree and even further. All of our cloud based infrastructure has been written as Terraform code with HCL, which meant adding a new node in the system, was as easy as copying the worker groups block in the EKS configuration, and setting the hardware properties of it. We could then easily deploy different services and deployments and have them run our public docker images. Brokers were also streamlined, and we could spin up a new broker within minutes. One area that we found a bit challenging to modify was perhaps the Databricks cluster, and the EKS ALB ingress (Nginx).

Certification management was also easily handled through Istio, local Cert-Manager and Let's encrypt. One area that could be taking a bit longer was the inclusion of private docker image secrets as a Kubernetes secret, and having it refreshed every 12 hours. To the best of our knowledge, cron jobs were the only way to achieve this.

On the other hand, bringin up a scalable Kafka cluster was not that difficult, but there were so many configurations that one can choose to turn on or amend. This can potentially affect modifiability in the long run, when the company might have varying and sometimes conflicting requirements.

Modifiability is also affected by the skillset of the engineers and how familiar they are with Kubernetes, Databricks and Istio.

Taking all these into consideration, we characterize system's modifiability as

follows (s is the skill set required);

$$Q_{\mathrm{M}} = S(K, D, K) \tag{4}$$

That is, the system modifiability is affected the Kubernetes maintenances (K), Databricks maintenances, versioning and configuration (D), and Kafka versioning, maintenance and configuration.

6.4. Tradeoff Points:

As a result of these analyses, we identifed two tradeoff points;

1. Event backbon and event brokers
2. Service mesh

One area that arose many worries is the event backbone. Event backbone being the communication facilitator has raised a lot of questions and many worried that this might turn into a bloated architectural component like enterprise service bus (ESB) in the service oriented architectures (SOAs). We addressed many of these questions and issues both in a dicussion and the prototype. Implementing event archive meant that if the event backbone went down, we could restore the previous state of affairs and bring services to the correct state. The implementation of circuit breakers through the event brokers further solidifed the avaiability quality attribute of the architecture and can deem to affect reliability too. Along the lines, event brokers helped us address some of the modifiability challenges. Having these event brokers setup meant that different environments do not implement their own event processing mechanism, and the interface is unified across. This clear interface contributed positively to the overall modifiability of the system and allowed engineers to simply copy the broker for their services. In addition, brokers also improved interoperability, and hard to trace bugs duge to event processor missmatch.

Given all, we do not prescribe architects to implement an event backbone or the broker in any given scenario. Cybermycelium does not tend to dictate what has to be done, or kill the creativity of the archites, but rather aims to

shed ligts on a novel perspective to designing BD systems. Therefore, the event backbone and event brokers intoruce tradeoff between performance, availability and reliability. Whereas eliminating the event backbone may increase avaiability longitudinaly, and increase modifiability cross-sectionally, it may affect the performance quality attribute in a negative way. This is due to the fact that the event backbone is distributed in nature, can scale well to account for demans, can cache and remember communication paths, and merge event streams, provide with windowing techniques, and be configured to facilitate certain access patterns that are common to the system.

Anothe area where stakeholders were challenged was the idea of service mesh. Whereas this makes a lot of sense to developers who had to figure out a twisted platform work, the benefit perhaps was not that evident to everyone from the beginning. This is another area of tradeoff. While having the service mesh affects the modifiability of the system in a negative way from platform point of view, it does increase it from the data engineer, software engineer point of view. The service mesh may also affect performance slightly, but the effect is negligible. Service mesh also affects avaiability quality attribute positively by streamlining the platform interfaces, providing an orchestrator (control tower), and doing health checks through proxies.

7. Limitation and future research

Cybermycelium is a new perspective to BD system development and tends to absorb many of the well practiced patterns and ideas from various domains. Being distributed in nature, there are still many areas in which Cybermycelium can improve. For instance, we still don't have a great answer to tail latency issues which can affect system negatively. Besides that, we recived feedbacks that many developers find Cybermycelium a complex architecture that require a lot of skill to implement. It requires the understanding of event-driven systems, event streaming, service meshing, data mesh, cloud computing and even data mesh. We do not think that a modern distributed BD architecture should

be simple, but we thrive to simplify the ways in which one can absorb Cybermycelium.

Taking all into consideration, we posit that distributed BD systems are still at infancy stage, and there's much work required to facilitate this area of research. These research could be in the areas of BD distributed patterns, event driven BD systems, data mesh, BD reference architecturse, and methods for creating BD distributed architectures.

Moreover, the security, privacy and metadata aspect of BD neeeds substantial work at macro and micro level. We need more mature technologies and better architectures that compose these technologies in a solution. This is one major area we have on our roadmap.

8. Conclusion

Data engineering is a complicated endevaour, and while there are many good practices for service distribution in software engineering, the BD domain does not seem to benefit from all of these ideas. This has made BD system development a daunting task, and many companeis have failed to bring to light the potential of data-driven decision making. Therefore, there is more and more research required in the areas of data architecture, and the ways in which the data flows between various components. RAs are a good start to such complicated tasks. By absorbing the best of knowledge from the practice and injecting it as a living model into practice, practitioners can benefit from already identified pitfalls. BD systems has got a long way to mature, but with clear direction both in the industry and academia, this aspiration can come to fruition in near future.

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